ANOMALOUS PRODUCTION OF FOURTH FAMILY UP QUARKS AT FUTURE LEPTON HADRON COLLIDERS

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Abstract

We investigate the production of fourth family up-type quarks using effective lagrangian approach at future lepton-hadron colliders and study the kinematical characteristics of the signal with an optimal set of cuts. We obtain the upper mass limits 500 GeV at THERA and one TeV at Linac $\otimes$ LHC.

I. INTRODUCTION

As is well known, the Standard Model (SM) with three families is in excellent agreement with experimental data available today [1]. But it leaves some open questions. At the most fundamental level, the number of fermion generations and the origin of their mass hierarchy are not explained by the SM. For these reasons, and others, several models extending SM have been proposed [2, 3, 4, 5, 6, 7]. Except the minimal SU(5) GUT all these models accommodate extra fermion generations [8, 9].

In the context of the search programs of future colliders, many analyses have been done for the production of fourth generation quarks at the linear [10, 11, 12] and at hadron colliders [13]. The potentials of the future lepton-hadron colliders in the new physics searches are comparable to those of the linear and hadron colliders [14]. Thus, in this study, we investigate the possibility of a single production of a fourth-family up quark (u_4) suggested by the effective lagrangian approach. In this approach the most general effective lagrangian, which describes the Flavour Changing Neutral Current (FCNC) interactions between u_4 and ordinary quarks, involving electroweak boson and gluon is given as follow [15, 16]:

$$\begin{aligned}\mathcal{L}_{eff} &= \sum_{U=u,c} i\frac{ee_U}{\Lambda}\kappa_{\gamma,u_4}\bar{u}_4\sigma_{\mu\nu}q^{\nu}UA^{\mu} + \frac{g}{2\cos\theta_W}\bar{u}_4[\gamma_\mu(v_{Z,U}-a_{Z,U}\gamma^5) + i\frac{\kappa_{Z,u_4}}{\Lambda}\sigma_{\mu\nu}q^{\nu}]UZ^{\mu} \\ &\quad + i\frac{g_s}{\Lambda}\kappa_{g,u_4}\bar{u}_4\sigma_{\mu\nu}q^{\nu}\frac{\lambda^i}{2}UG^{i\mu} + h.c.,\end{aligned}$$

where $\sigma_{\mu\nu}$=(i/2)[γ^μ , γ^ν], θ_W is the Weinberg angle, q is the four-momentum of the exchanged boson; e, g and g_s denote the gauge couplings relative to U(1), SU(2) and SU(3) symmetries, respectively; e_U is the electric charge of up-type quarks, A^μ, Z^μ and $G^{i\mu}$ the fields of the photon, Z boson and gluon, respectively; and Λ denotes the scale up to which the effective theory is assumed to hold. By convention, we set Λ=m_4, mass of the fourth family quark in following.

II. THE ANOMALOUS PRODUCTION OF FOURTH FAMILY UP QUARK

Parton level subprocess responsible for the u_4 production in ep collisions is $eq \to eu_4$. The kinematics of this process is same as that of the single top quark production via FCNC interactions, which was presented in one of our earlier works [17]. Here, we present the total production cross sections as functions of u_4 mass in Fig. 1 and Fig. 2. In Fig. 1, we display

the cross sections as functions of the mass of u_4, at future lepton-hadron collider THERA with the center of mass energy $\sqrt{S}$= 1 TeV and with the luminosity of $\mathcal{L} = 4.10^{30}$ cm^{-2}s^{-1} [18]. Fig. 2 shows the behaviour of the cross section as a function of m$_4$ at Linac $\otimes$ LHC with $\sqrt{S}$= 5.3 TeV and with the luminosity of $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1} [19]. In these figures the lower lines correspond to the photonic channel only and the upper lines correspond to the sum of γ and Z exchange diagrams. Graphs in Fig 1 and 2 were computed by taking the anomalous coupling values $\kappa_\gamma = \kappa_Z = 0.1$ for illustration. In obtaining the mentioned behaviour of the cross sections we have taken into account of both up and charm quark distributions [20, 21]. The charm quark is present inside the proton as part of the quark-antiquark sea and gives considerable contribution to the cross section.

We assume the anomalous decays of u_4 quark to be dominant, which is different from the case of top-quark decays where the SM decay mode is dominant. In Table I, we present the branching ratios and the total decay widths of u_4 quark via anomalous interactions. SM decay modes are negligible for $\kappa/\Lambda > 0.01$ TeV^{-1} due to the small magnitude of the extended CKM matrix elements $V_{u_4 b}$ [22, 23].

In order to enrich the statistics for the experimental observations of the signal we also take into account $\bar{u}_4$ production through the subprocess e$\bar{q}$ $\rightarrow$ e$\bar{u}_4$. The contribution of this process is relatively small when compared with the u_4 production due to the sea quark distribution in the proton. Tables II and III present the total production cross sections of u_4 and $\bar{u}_4$ in addition to the number of signal and background events in various decay channels of u_4 at THERA and Linac$\otimes$LHC, respectively.

When the fourth family u_4 (or $\bar{u}_4$) quarks are produced, they will decay via FCNC interactions giving rise to the signal $e^- qV$, where $q = u, c, t$ (or $\bar{u}, \bar{c}, \bar{t}$) and V denotes the neutral gauge bosons γ, Z, g.

We consider the relevant backgrounds from the following subprocesses:

$$eq \rightarrow eq\gamma$$

$$eq \rightarrow eqZ$$

$$eq \rightarrow eqg$$

where $q = u, c$ (or $\bar{u}, \bar{c}$). The cross sections for these backgrounds are shown in Table II (at THERA) and Table III (at Linac $\otimes$ LHC) for the minimal cuts $p_T^{e,\gamma,j} > 10$ GeV and optimal cuts $p_T^{e,\gamma,j} > 20$ GeV and $M_{qV} > 250$ GeV on the final state particles. From Table

II we conclude that the number of signal events for $u_4 \to gq$ and $u_4 \to Zq$ (q=u,c) channels is promising, which makes it possible to observe a u_4 production signal at the THERA, especially for low lying u_4-quark mass values (300-500 GeV). As can be seen from Table III, it will be possible to observe the anomalous production of u_4 quark in all decay channels if the corresponding backgrounds is kept at a low level at Linac $\otimes$ LHC collider. We found that u_4 production signal at this machine is observable down to the anomalous coupling $\kappa_{V,u_4} = 0.01$ at the mass of u_4-quark about 700 GeV. For the channels including top quark in the final state ($e^- Vt$) we obtain very low number of background events, therefore we have not shown them in Tables II and III.

Assuming Poisson statistics, we use the significance formula $S/\sqrt{B} \geq 3$ for signal observation at the 95% C.L., where the number of signal and background events S and B are calculated by multiplying the cross section with corresponding branching ratios depending on the decay channels and the integrated luminosities of the colliders considered.

III. CONCLUSION

In this study, we have considered the anomalous single production of fourth family up-quarks via the FCNC couplings at future ep colliders. We have shown that the reaction $eq \to eu_4$ can take place at an observable rate at these colliders. Hence, the fourth family up-quark will manifest itself at THERA and Linac $\otimes$ LHC with masses below 500 GeV and 1 TeV, respectively. Thus the future lepton-hadron colliders have promising potential in searching for manifestations of non-standard physics.

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TABLE I: Branching ratios (%) and total decay widths of u_4 quark depending on its mass ($\kappa_{\gamma,u_4} = \kappa_{Z,u_4} = 0.1$, $\Lambda = m_{u_4}$)

Mass (GeV)	$gu(c)$	gt	$Zu(c)$	Zt	$\gamma u(c)$	γt	Γ(GeV)
300	3.1	0.9	70.5	25.2	0.1	0.04	7.15
400	1.4	0.8	61.1	36.6	0.07	0.04	20.12
500	0.8	0.6	57.3	41.2	0.04	0.03	42.31
600	0.5	0.4	55.2	43.8	0.03	0.02	76.29
700	0.4	0.3	53.9	45.4	0.02	0.02	124.45

TABLE II: Number of signal and background events in various decay channels of u_4 quark at THERA with $\sqrt{S} = 1$ TeV and $L = 40$ pb^{-1} with corresponding total cross section in pb. B$_1$ and B$_2$ denote the number of background events with the cuts ($p_T^{e,\gamma,j} > 10$ GeV) and ($p_T^{e,\gamma,j} > 20$ GeV, $M_{Vq} > 250$ GeV), respectively.

Mass (GeV)	$gu(c)$	gt	$Zu(c)$	Zt	$\gamma u(c)$	γt	$\sigma_{tot}(eu(c) \to eu_4)$	$\sigma_{tot}(e\bar{u}(\bar{c}) \to e\bar{u}_4)$
300	12.4	3.6	280.1	100.3	0.56	0.17	6.67	3.26
400	4.1	2.2	176.6	105.8	0.20	0.10	4.57	2.66
500	1.7	1.2	117.8	84.6	0.08	0.06	3.02	2.12
600	0.7	0.6	75.9	60.1	0.04	0.03	1.88	1.55
700	0.3	0.3	43.3	36.4	0.02	0.01	1.05	0.96
B$_1$	17440	-	6.7	-	1152	-		
B$_2$	20.3	-	1.3	-	41.2	-		

TABLE III: Number of signal and background events in various decay channels of u_4 quark at Linac⊗LHC with $\sqrt{S} = 5.3$ TeV and $L = 10^4$ pb^{-1} with corresponding total cross section in pb. B$_1$ and B$_2$ denote the number of background events with the cuts ($p_T^{e,\gamma,j} > 10$ GeV) and ($p_T^{e,\gamma,j} > 20$ GeV, $M_{Vq} > 250$ GeV), respectively.

Mass (GeV)	$gu(c)$	gt	$Zu(c)$	Zt	$\gamma u(c)$	γt	$\sigma_{tot}(eu(c) \to eu_4)$	$\sigma_{tot}(e\bar{u}(\bar{c}) \to e\bar{u}_4)$
300	6423.1	1835.2	144692.4	51786.5	286.7	86.0	13.97	6.54
400	2696.1	1423.3	115137.5	68945.8	131.1	65.5	13.06	5.78
500	1459.8	984.3	101194.3	72720.7	70.9	50.0	12.36	5.29
600	890.8	681.2	91990.9	72926.4	45.8	34.9	11.74	4.92
700	592.3	488.3	85088.9	71614.7	30.4	25.4	11.15	4.63
B$_1$	1.9×10^7	-	1.2×10^4	-	1.4×10^6	-		
B$_2$	6.5×10^4	-	3.3×10^3	-	5.1×10^4	-		

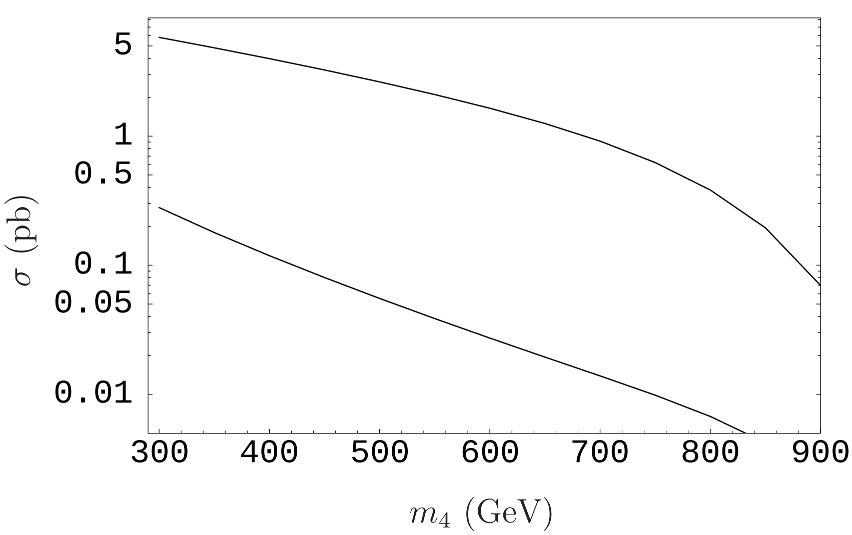

FIG. 1: Photonic (lower line) and total (upper line) production cross section for the FCNC single u_4 at$\sqrt{S}$=1 TeV as a function of m$_4$ with $\kappa_\gamma = 0.1$ and $\kappa_\gamma = \kappa_Z = 0.1$, respectively.

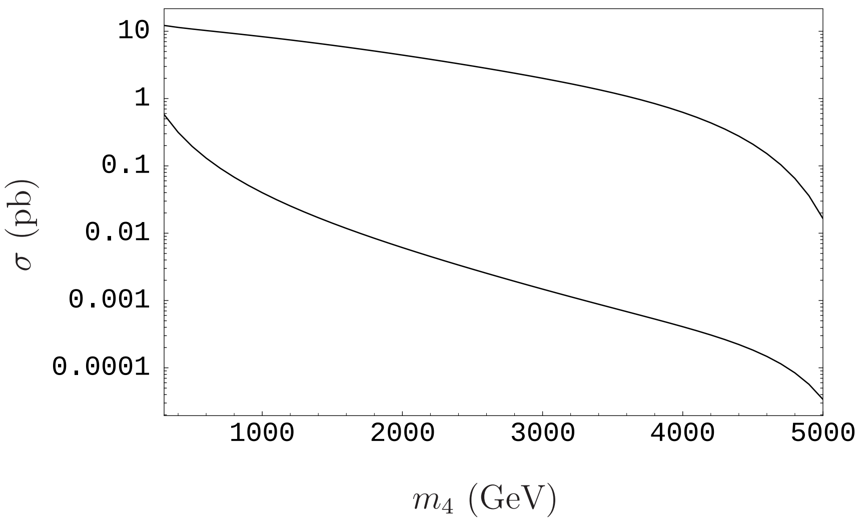

FIG. 2: Photonic (lower line) and total (upper line) production cross section for the FCNC single u_4 at $\sqrt{S}$=5.3 TeV as a function of m_4 with $\kappa_\gamma = 0.1$ and $\kappa_\gamma = \kappa_Z = 0.1$, respectively.